Tracking and Ground Based Navigation: A Description of the Weather Project

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The Weather Project forms part of an overall Radio Systems Development Project which seeks to optimize the spacecraft-to-ground communications link. In order to meet the future requirements of the planetary exploration program, a study of, inter alia, weather-dependent characteristics of X- and K-band propagation through the atmosphere is imperative. The objective of the Weather Project is, therefore, the statistical prediction of the performance of the DSN at X-band, and in the future at K-band.

This article discusses the general approach of the Weather Project, the measurements, the calibrations, the equipment, and the methods. Problems encountered are also discussed as well as the proposed future work.

I. Introduction

The Weather Project forms part of an overall Radio Systems Development Project which seeks to optimize the spacecraft-to-ground communications link. In order to meet the future requirements of the planetary exploration program a study of, *inter alia*, weather-dependent characteristics of X- and K-band propagation through the atmosphere is imperative. Statistical correlations of weather and communications capability at X- and K-bands are needed to provide practical predictions of link performance for these missions. The objective of the Weather Project is, therefore, the statistical prediction of the performance of the DSN at X-band, and in the future at K-band.

This article discusses the general approach of the Weather Project, the measurements, the calibrations, the equipment, and the methods. Problems encountered are also discussed as well as the proposed future work. A preliminary analysis of the results for calendar year 1971 will be presented in a subsequent article.

II. Previous Data

Prior to the start of the Weather Project, no K-band system was available in the DSN, and the only suitable X-band data for the DSN was the information contained in the Deep Space Network/Flight Project Interface Design Handbook (Ref. 1). These data were derived primarily from a contractor report submitted to JPL (Ref. 2) which calculated signal attenuation due to cloud cover from meteorological measurements. The meteorological data for Goldstone were taken from soundings at Dagett, California and from Edwards Air Force Base. Figure 1, which is taken from Ref. 1, shows the form of these data. The figure shows calculated relative increase in system temperature due to cloud cover at DSS 14 as a function of elevation angle for one percent probability conditions. The Weather Project thus requires experimental data, both microwave and meteorological, taken at the 64-m-diameter antenna sites.

III. General Plan

The general plan of the project is discussed in this section. The Earth's atmosphere, particularly changing weather conditions, has many effects on a microwave signal travelling through it. In the microwave bands of interest to space communications, these effects are primarily atmospheric noise which degrades the ground system sensitivity and attenuates the received or transmitted signal. In the bands of interest these effects are due primarily to water vapor, clouds, and liquid water or ice. Wind can also degrade system performance in at least two ways. This will be considered separately and is not treated in this article.

Microwave system temperature measurements at S-, X-, and K-bands are being made and recorded at DSS 14. Ground level meteorological measurements are also recorded at DSS 14. Studies will be performed to correlate the microwave and meteorological data. Meteorological parameters important in establishing X-band performance will be identified. The experimental data will yield short-term X-band performance (noise temperature and attenuation) statistics, which will assist in the development of the elements of a transfer function or functions H, which will transform meteorological data into X-band performance data. The transfer function will be tested against measured microwave and meteorological data. The probability distributions of the transfer function will then be derived.

Experimental K-band data are recorded at DSS 14 to give further insight into the X-band problem as well as to provide K-band performance specifications in the future. S-band data are recorded at DSS 14 not only for further insight into X-band problems, but also to help with the problem of deriving X-band performance statistics for the overseas 64-m antenna sites at an early date.

DSS 43 and DSS 63 will soon be operational, and it will be possible to record S-band data at these sites. No X-band systems will be available at DSS 43 or DSS 63 until about January 1975. This will not allow sufficient X-band data to be recorded at these stations before their preliminary X-band performance statistics are required. Hence, it is proposed to record S-band data at DSS 14, 43, and 63 as well as meteorological data at all these stations. Studies are underway to investigate the feasibility of predicting overseas X-band performance statistics from recorded S-band and meteorological data. These studies will be reported later.

IV. Equipment, Measurements, and Methods

Experimental data are being taken only at DSS 14 at this time. The following measurements are being made and recorded in analog form: (1) microwave: system operating noise temperature T_{op}, and antenna elevation angle θ, as functions of time; and (2) meteorological: ground air temperature and humidity, barometric pressure, wind speed and direction, and rainfall.

The X-band system in the multifrequency X- and K-band (MXK) cone is used as a total power radiometer, and the output is recorded as a function of time on a strip chart recorder, along with antenna elevation angle. This system operates 24 hours per day or as close to this as is possible in practice. In order to calibrate the system and to remove the effects of the slow gain drifts that are experienced, an automatic waveguide switch controller was set up to switch the system between the antenna and the ambient load in the time ratio 55 minutes to 5 minutes. Furthermore, a short calibration is performed manually approximately once per day. This procedure sets the detector and recorder scales, and adjusts the zero positions and calibrates T_{op}.

The advantages of using the X-band system in the MXK cone for the Weather Project are several. An existing system is being used, and experience is being gained in its operation by JPL and Goldstone personnel. Weather data are recorded not only when the antenna is at zenith but also when the station is tracking spacecraft at S-band. This yields atmospheric data at elevation angles typical of tracking operations, and it is also cost effective.

The preliminary data analysis consists of determining for what period of time T_{op} increases over that value to be expected in clear, dry weather, at the given antenna elevation angle of each data point, and by how much. The results, presented in statistical and graphical form, report increases in T_{op} due only to atmospheric effects, as far as this is possible, and as a function of elevation angle and time of year. Further data analysis will correlate meteorological data with the microwave data as well as deriving atmospheric attenuation as functions of elevation angle and time of year. These experimental data will be compared with the theoretical predictions of Refs. 1 and 2.

S-band and K-band radio metric data have recently been added to the recording system for the reasons discussed above. Various problems have militated against these data being recorded on a 24-hour per day basis. For example, when the station is tracking a spacecraft two-way through the polarization diversity S-band (PDS) cone, it is not possible to connect the S-band Megawatt Transmit (SMT) maser to the SMT horn, as this is a forbidden waveguide switch position to protect the SMT maser from the S-band transmitter. S- and K-band microwave data are therefore recorded on a best effort basis.

In order to improve both the dynamic range and the resolution of the measurement of T_{op}, a digital data acquisition and recording system has been investigated. A preliminary version (see Fig. 2) has been implemented and operated in parallel with the analog recordings. Data are recorded once per minute and the system has a capability of 10 simultaneous channels and 12 status indicator channels. The recording is on magnetic tape with a paper tape printout for real-time monitoring. The analog recordings are considered as a back-up to the digital recordings when operated in parallel with them. X- and K-band radio metric data have been implemented in the digital system as well as antenna elevation angle, day number and time, ground air temperature, and humidity. Consideration is being given to the digital recording of the other measured parameters as well as improvements to the digital system.

V. Calibrations and Problems

Any receiver gain change is indistinguishable in the radiometer output from a change in atmospheric noise temperature. As the maser gain drifts in a period of several hours, it is necessary to make gain calibrations continually. For this purpose an automatic waveguide switch controller was set up, as stated above, to switch the radiometer between the feedhorn and a waveguide ambient load. Another switch position was a zero reference calibration point. These calibrations consumed only five minutes in every hour.

The reliability of the timing and control circuits of this automatic switch proved to be a problem, and calibration capability was lost when the physical temperature of the ambient load was not recorded. Furthermore the analog recording system was required to record a dynamic range of at least 30 K to 300 K. This severly restricted measurement resolution and prompted an investigation into other measurement methods. The possibility of using a noise-adding radiometer (NAR) (Ref. 3) developed at JPL for recording the weather data is now underway. This will stabilize the radiometer gain, increase dynamic range, and it is expected that the use of the NAR will also improve the accuracy of the weather data as well as facilitate data reduction. Consideration is now being given to improving the data system to avoid the effects of drifts in the digital recording equipment.

One of the prime calibration problems is the determination of a "normal" system temperature profile. The normal or baseline system temperature is that elevation profile which obtains in clear, dry weather and against which atmospheric degradation is measured. The normal profile, however, is a function of both frequency and position of the subreflector. The prime X-band frequency is 8415 MHz, which is the frequency for the *Mariner* Venus–Mercury S/X experiment. A considerable portion of X-band radio science, however, is carried out at 7850 MHz, where the normal profile is different from that at 8415 MHz. Figure 3 shows "fair weather" elevation profiles for S-, X-, and K-bands, with the subreflector correctly positioned in each case. Figure 4 shows X-band "fair weather" profiles for 7850 MHz and 8415 MHz with the subreflector focused on the SMT cone. The 8415-MHz profile with the subreflector positioned on the PDS cone is not identical to the 8415-MHz/SMT profile shown in the figure. Figure 5 is a symbolic representation of a possible explanation for the effect of the misaligned feed system profile. The solid ray paths are drawn for the subreflector positioned on the right-hand cone, and the dotted ray paths obtain for the left-hand cone. This shows the left-hand cone receiving some ground radiation. The antenna moves in elevation in the direction of the arrow only, and therefore at low elevation angles the misaligned feed system is expected to have a slightly lower system temperature because some spillover ground reflections will not be received.

The normal profile is also a function of rotation in azimuth, but this is a smaller effect and will be taken into account in a more detailed analysis of the data. The calibration of the misaligned antenna beam will be carried out by radio astronomical methods; preliminary measurements on the Moon have been made, but further measurements using radio sources are required.

Another problem which complicates the calibration and measurement of data is interference. Interference is experienced in several forms. The first is a CW signal from certain X-band microwave communications links inside the maser passband. This problem has been temporarily solved by suitable filtering. The other forms of interference are noise bursts, which are presently under investigation, and the interference from the fourth harmonic of the S-band transmitter. Figure 6 shows *Mariner* Venus–Mercury 1973 S/X frequencies. The S-band transmit frequency is 2113.3 MHz, and the ranging sidebands are shown in the figure in relation to the S-band receive frequency 182 MHz away. The fourth harmonic of the S-band transmitter is shown 38 MHz higher than the center of the X-band passband, and the fourth harmonic of the S-band ranging modulation is shown approaching this passband. In certain circumstances interference from the fourth harmonic of some ranging modulation has contaminated the X-band weather data. This problem is also presently under investigation.

VI. Future Work

Previous studies (Ref. 2) have shown that cloud cover has a significant effect on X-band systems. The parameters of importance for microwave transmission and noise generation are the concentration and size distribution of the scattering particles, their ice versus water characteristics, and the temperature and depth of the layers containing the particles. Observations of these cloud parameters are not made on a routine basis. Cloud cover is generally reported at few locations in the Mojave area and then in such broad categories as to be of questionable value.

In order to gain meaningful microwave correlations with cloud cover in the antenna beam, it is proposed to install a camera on the boresight axis of the 64-m antenna. Color photographs will be taken on a routine basis with automatic turn-on, shut-down, aperture adjustment, and synchronization with day and time. A meteorological analysis of these data will provide more meaningful correlations with the microwave data. An infrared radiometer will be investigated for cloud data at night.

The variable component of atmospheric thermal emission near 22 GHz is dominated by emission from water vapor, which has a resonant line at 22.235 GHz, and by emission from condensed water which exists in clouds and precipitation (Ref. 4). It is theoretically possible to measure total integrated water vapor in the antenna beam and to separate the effects of condensed water (Refs. 5 and 6). Two radiometers have been used for this measurement, one at or close to the water line and the other well off the line center. The frequency of the second radiometer may be either higher or lower than the line center.

As there are several reasons for measuring liquid water and water vapor in the atmosphere, radiometers for this purpose will be investigated. These measurements would add valuable information to the meteorological aspects of the project, particularly as measurements could be made in the line of the antenna beam. Furthermore, the vapor measurements could yield an on-line correction for phase, which would be important at critical times for certain spacecraft experiments as well as for the radio science experiments planned by JPL. The differential signal phase change between S- and X-band, through the Earth's atmosphere, due to water vapor, is important for the S/X experiments and is presently being studied. Finally, the greatest uncertainty in spacecraft tracking after the introduction of Differenced Range Versus Integrated Doppler (DRVID) and X-band will be the troposphere. A worthwhile project would be to correlate doppler and range residuals with total integrated water vapor and liquid water in the antenna beam.

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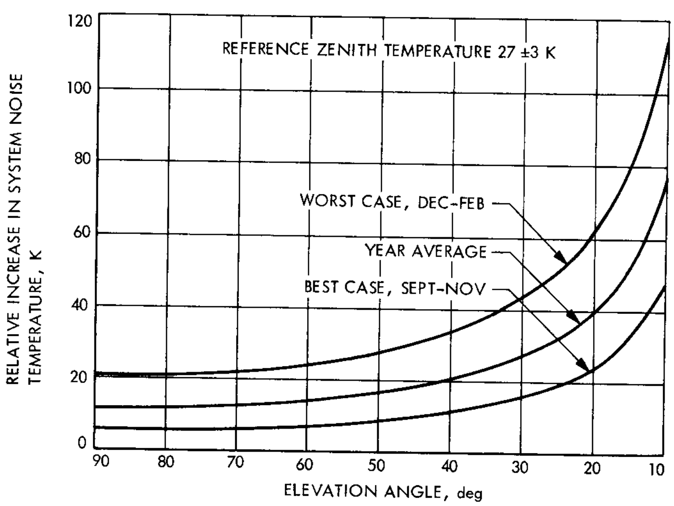

Fig. 1. Increase in system noise temperature at X-band due to cloud cover at DSS 14 for calculated one percent probability conditions

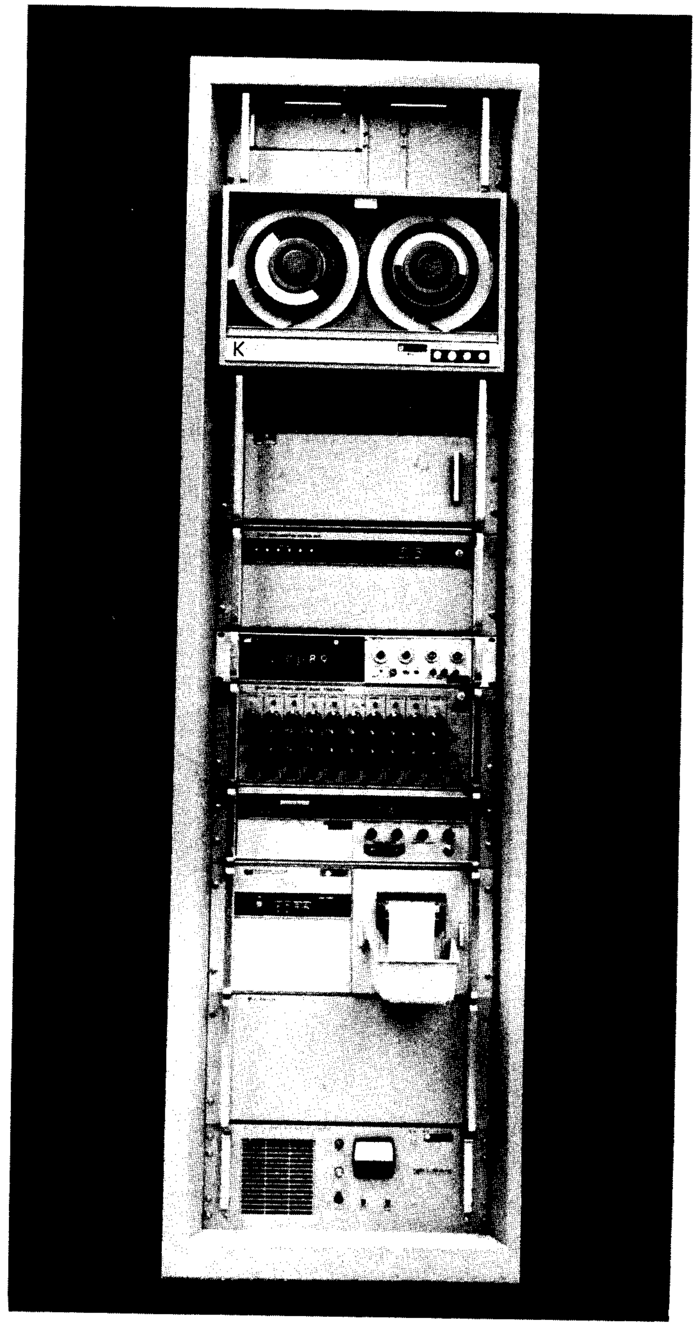

Fig. 2. Preliminary version of data acquisition and recording system

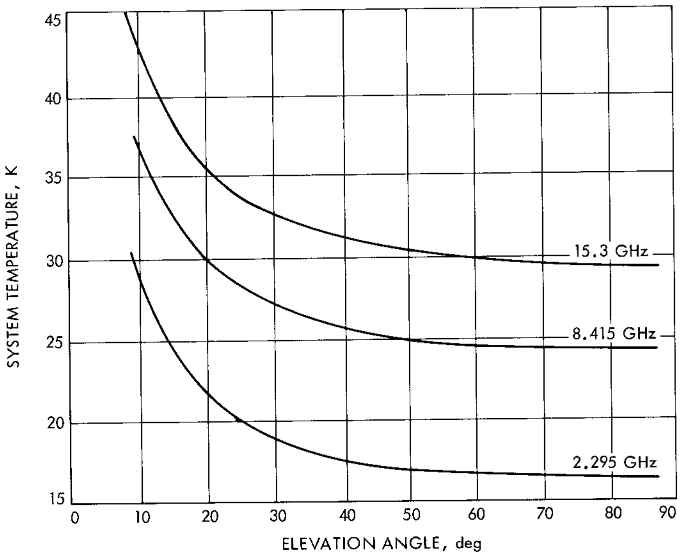

Fig. 3. DSS 14 elevation profiles at S-, X-, and K-bands

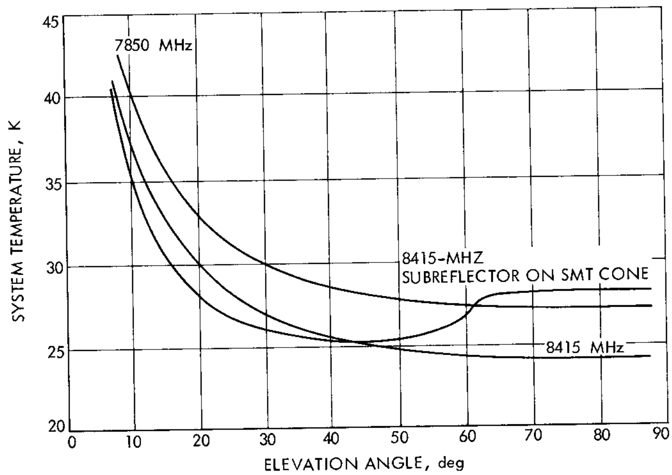

Fig. 4. The effect of frequency and subreflector position on X-band profiles

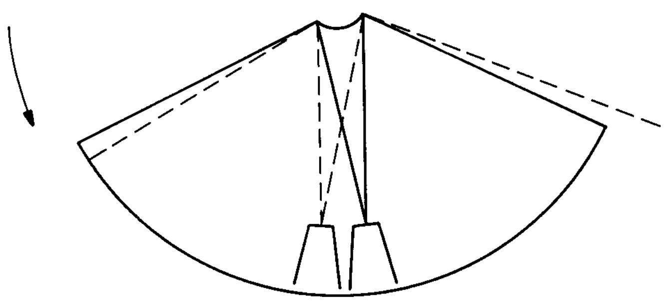

Fig. 5. The effect of misaligned feed system

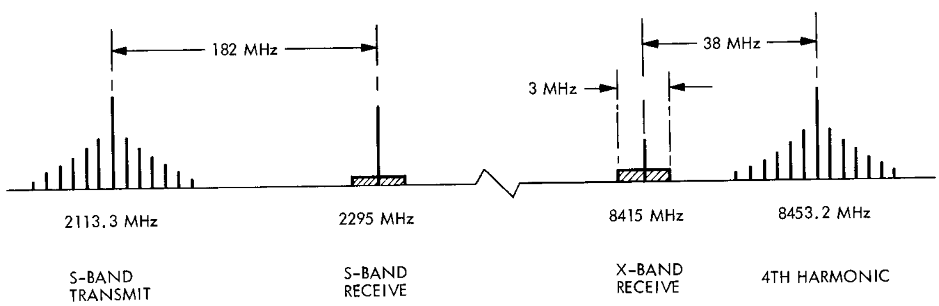

Fig. 6. Mariner Venus–Mercury 1973 S/X frequencies